Virginia Tech ◆ ECE/CS 5565, Network Architecture and Protocols I ◆ Fall 2024

Project 5: Exploring TCP Congestion Control with OMNeT++/INET and Wireshark

(A list of updates is at the end of the assignment.)

Introduction

In this project, you will examine TCP congestion control using simulation with OMNeT++/INET. You will, also, examine simulation results using Wireshark. The project consists of three parts.

- Part 1: Analyze basic performance
- Part 2: Analyze TCP congestion control behavior
- Part 3: Submit the project report

Before starting on the project, read through this assignment to know how work in different parts fits together. Also, review the class syllabus, especially sections on “Assessments,” “Grading,” “Late and Missed Work,” “Grading Questions," and “Graduate Academic Integrity.”

Simulation Model

You will use and modify **package.ned** and **omnetpp.ini** files that are provided to you to examine the performance of a simple network in four different scenarios. Figure 1 shows the `RoutedNetwork` model as specified by **package.ned**. The network consists of six hosts and one server which are connected routers through three Ethernet switches. The Ethernet switches then connect through three routers. The link from `router1` and `router3` is configured to create congestion scenarios.

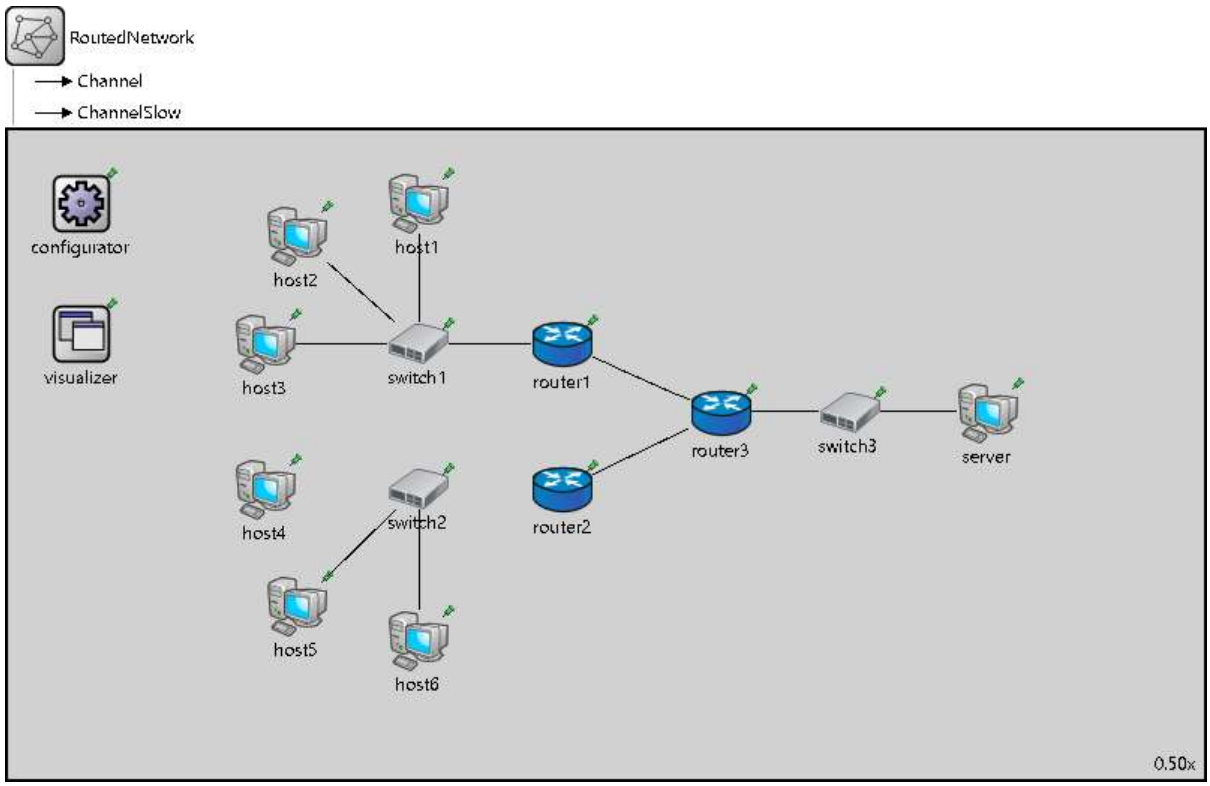

Figure 1. View of RoutedNetwork in the OMNeT++/INET IDE.

Use the OMNeT++ IDE to examine the **package.ned** and **omnetpp.ini** files before doing any modifications or simulations to ensure that you understand the key aspects of the network and its configuration. Note the following in each of the files.

- Two different channel models are defined in **package.ned**, `Channel` and `ChannelSlow`. `Channel` is a 100-Mbps instance of a `ThruputMeteringChannel` as was used in Project 3. `ChannelSlow` is a 10-Mbps instance of a `ThruputMeetingChannel`. You will use the `per` parameter to set a packet error rate for `ChannelSlow`. `ChannelSlow` is used only for the link between `router1` and `router3`. It is difficult to create actual congestion on a link in the simulator, so you will set parameter `per` to introduce packet errors to cause lost packets that will invoke TCP congestion control. Note that `per` = 0.01 leads to a 1% packet error rate. For both `Channel` and `ChannelSlow`, you can set the `thruputDisplay` format to control what is displayed for the links during simulation.
- `Ipv4NetworkConfigurator` is used to perform all network and router configuration and all addressing is with IPv4. Note that the `ipv4.arp.typename` parameter in **omnetpp.ini** file is set to pre-load ARP tables at all hosts, so there will not be any ARP message sent during simulation.
- The `tcp.tcpAlgorithmClass` parameter in **omnetpp.ini** sets the version of TCP to be used at each host. Note that the "`*.*`" in front of `tcp.tcpAlgorithmClass` causes the parameter to be applied at all devices in the model where there is a TCP module. This same wildcard naming scheme is used with some of the other settings in **omnetpp.ini**. Also in **omnetpp.ini**, the TCP maximum segment size (MSS) is set to 1,460 bytes by the `tcp.mss` parameter.
- All hosts, `host1` through `host6`, run the `TcpSessionApp` application that connects to the `TCPEchoApp` application at `server`. 2 MB of data are sent by each of the hosts. The server sends all received data back to the sending host.
- Performance analysis will be based on results at `host1` which is affected by the "slow" link between `router1` and `router3`. The other hosts are included to provide competing traffic in the network. Network traffic at `host1` is captured by a PCAP recorder. After each simulation, the file **host1.pcapng** will contain a packet trace that can be examined in Wireshark.

Part 1: Analyze Basic Performance

Part 1 examines the performance of the network under four different conditions. Simulate four versions of the model by modifying **package.ned** and **omnetpp.ini** files to examine performance of the TCP connection between `host1` (Host 1) and `server` (Server). The four scenarios are:

1) the operation of TCP without congestion control and with no "congestion," i.e. no errors on the link between `router1` (Router 1) and `router3` (Router 3);
2) the operation of TCP without congestion control and with "congestion," i.e. with errors on the link between Router 1 and Router 3;
3) the operation of TCP Tahoe, which includes congestion control, and with no "congestion," i.e. no errors on the link between Router 1 and Router 3; and

4) the operation of TCP Tahoe with "congestion," i.e. with errors on the link between Router 1 and Router 3.

Results from each run of the simulator and analysis of the **host1.pcapng** file for each simulation run can be used to gain insight into relative performance for the four different scenarios. Note that these results do not have statistical significance as we are looking at just one run for each scenario. There are better ways to do simulation with an appropriate start-up period, multiple samples of metrics of interest, and statistical analysis using confidence intervals that would yield more credible results.[1] Nonetheless, we can still observe trends and gain insight from the simulation results for this project.

Our simulation experiment considers two factors, the TCP version and the packet error rate on the Router 1-Router 3 link, each with two levels or settings. The levels for the TCP version are `TcpNoCongestionControl` (TCP has no congestion control) and `TcpTahoe` (Tahoe version of TCP). Perform four simulation runs with the four possible combinations of the `per` parameter for the `ChannelSlow` model in **package.ned** and the `tcp.tcpAlgorithmClass` parameter in **omnetpp.ini**.

For this part of the project, you are to include the following items in the project report.

1.1. Include a table showing basic performance results for the TCP connection between Host 1 and Server using the format shown in Table 1 below. The "TCP" column indicates the version of TCP used in the run. The "R1-R3 PER" column indicates the packet error rate on the link connecting Router 1 and Router 3. An Excel file with this table is provided. For the throughput, consider the throughput from Host 1 to Server. Briefly summarize how you obtained the results.

Table 1. Basic Performance Results for TCP Connection between Host 1 and Server

Run	TCP	R1-R3 PER	Mean Delay (s)	StdDev Delay (s)	Throughput (kbps)
1	NoCongestionControl	0.00			
2	NoCongestionControl	0.01			
3	Tahoe	0.00			
4	Tahoe	0.01			

1.2. Include an image of the histogram of end-to-end delay at Host 1 for each run. Clearly label the run and the factor values (type of TCP congestion control and packet error rate) for each graph.

1.3. Briefly compare results from different scenarios as follows. Refer to specific results in the table and to specific features of the histograms in your comparisons.

1.3(a) Compare Run 1 to Run 3 (different TCP versions with no errors). Does one perform markedly better than the other? If so, why? If not, why not?

1.3(b) Compare Run 2 to Run 4 (different TCP versions, with errors). Does one perform markedly better than the other in coping with packet loss and perceived congestion? If so, why? If not, why not? What features of TCP Tahoe help or hurt the performance of Run 2 compared to results for Run 4.

[1] A more rigorous approach to network simulation will be covered in ECE/CS 5566 in Spring 2025.

1.3(c) Compare Run 1 to Run 2 (both with no TCP congestion control, but without and with errors). Does one perform markedly better than the other? If so, why? If not, why not?

1.3(d) Compare Run 3 to Run 4 (both TCP Tahoe, but without and with errors). Does one perform markedly better than the other? If so, why? If not, why not?

1.3(e) Briefly summarize the comparisons. What general insights can be gained from the results of this simulation experiment?

To answer the questions above, take the following steps for each run (each combination of factors) to provide the information requested above.

- Modify and verify the settings of parameters `per` and `tcp.tcpAlgorithmClass` as needed for the run. Then run the simulation. After running the simulation, use the log to verify that 2 MB of traffic was transferred for each of the six hosts.
- Create and examine the **general.anf** file similar to what was done in Project 1. Use the Browse Data tab and the Result Name Filter function to search for Host 1 results for "endToEndDelay:histogram." By selecting the results for Host 1, you can see the values for the mean delay and standard deviation of delay in the Properties window in the OMNeT++ IDE. Double clicking on the results for Host 1 causes the histogram to be generated. You can right-click on the graph and select Save Image… to save an image of the graph.[2]
- Save each separate copy of **host1.pcapng** for each run using names that identify the run with which each is associated. You can find the throughput value for Question 1.1 by using the Statistics > Conversations menu in Wireshark to find the throughput from Host 1 to Server. Note that the port number is a good way to identify Server versus Host 1. The application at Server is assigned port number 1000 in **omnetpp.ini**, so packets coming from port 1000 are from Server and packets going to port 1000 are from Host 1. You will need to use the **host1.pcapng** file for Run 4 (TCP Tahoe with errors) for Part 2 of the project.

Part 2: Analyze TCP Congestion Control Behavior

Part 2 uses the **host1.pcapng** file for Run 4 (TCP Tahoe with errors) to examine the behavior of TCP congestion control. Include answers to the following questions in your project report.

2.1. Find the first frame from Host 1 to Server in the trace where Wireshark indicates "TCP Window Full." Answer the following questions.

2.1(a) What is the frame number for the TCP segment from Host 1 to Server marked "TCP Window Full"?

2.1(b) Examine the TCP protocol information to find the Window size and the bytes in flight (look in the "SEQ/ACK analysis" area). What is the effective window for the client sending to the server? Show your calculation.

2.1(c) Examine the previous frame that sent data from the client to the server. What is the effective window for that frame? Show your calculation.

[2] As an aside, the OMNeT++ IDE will save the histogram using the Scalable Vector Graphics (SVG) format, which is based on XML. Use a text editor to examine one of the SVG files to see an example of how and XML-based format is used for data representation.

2.1(d) What mechanism is keeping the client from sending more data immediately? Briefly justify your answer.

2.2. Find the first frame from Server to Host 1 that is marked "TCP Previous segment not captured" by Wireshark. This text indicates that this packet was received out of order at Host 1. Answer the following questions.

2.2(a) What is the frame number for the TCP segment from Server to Host 1 marked "TCP Previous segment not captured"?

2.2(b) Based on sequence numbers and acknowledgments, what bytes from Server are missing at Host 1? Briefly explain how you derived this answer.

2.2(c) Look at the first acknowledgement from Host 1 back to Server that follows the frame marked "TCP Previous segment not captured." What is Wireshark telling us about this TCP segment? Briefly explains what this means.

2.2(d) Note that the "Ack" value in TCP segments from Host 1 to Server are not advancing for multiple segments after the missing segment. Find the TCP segment from Server to Host 1 that finally sends the missing data. What is this frame number?

2.2(e) What is Wireshark telling us about this TCP segment? What TCP behavior is being invoked?

Open the graph of TCP Sequence Numbers (Stevens) by using the Statistics > TCP Stream Graphs > Time Sequence (Stevens) menu in Wireshark. It should look something like the window in Figure 2. Make sure that the graph is for segments going from Server (using port 1000) to Host 1. If reversed, click on the Switch Direction button. You may also need to select a different stream if you are not seeing a plot similar to what is shown in Figure 2.

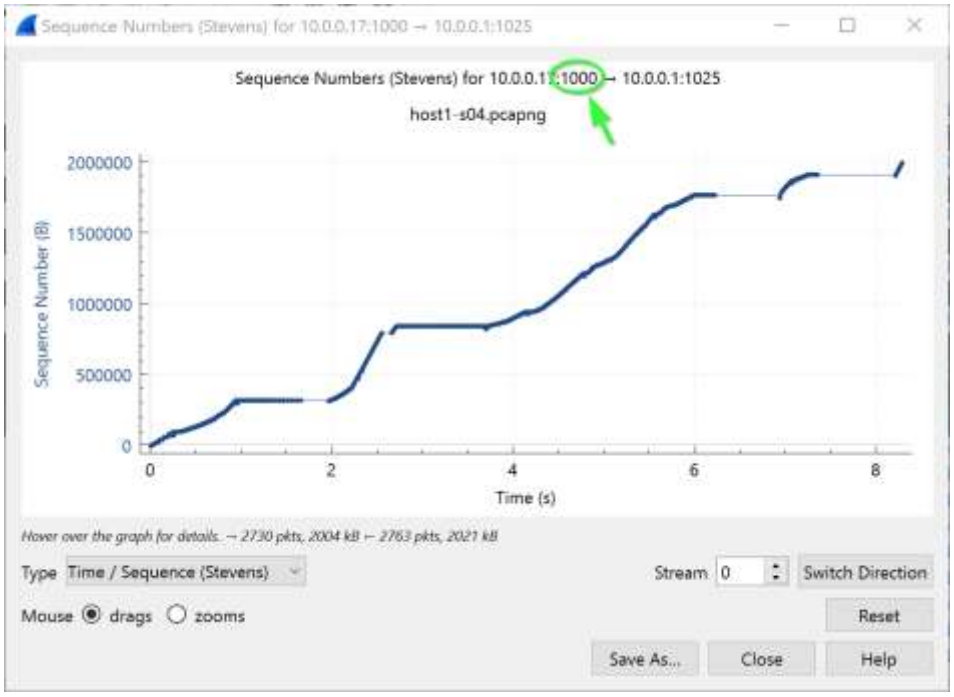

Figure 2. Plot of TCP Sequence Number (Stevens) in Wireshark. As indicated by the circled text and arrow, the graph is for TCP segments sent by Server which is using port 1000.

2.3. Find the frame in the graph that was identified in Question 2.2(d). You can put the mouse (in "drags" mode) over dots (each representing a TCP segment) in the graph to find the Wireshark frame number. Zoom in so that the individual dots are visible, the dot of interest is near the center of the visible graph, and time = 0 is still visible. Using the graph, answer the following questions.

2.3(a) Include an image of the zoomed-in graph report in your report. An image can be saved using the Save As… button from the Wireshark graph window. Add an arrow to the image to clearly point to the dot representing the TCP segment of interest which corresponds to the TCP segment identified in Question 2.2(d).

2.3(b) Generally speaking, what is TCP's mode of operation to the left of the dot of interest? Briefly justify your answer. Reference both facts about the operation of TCP Tahoe and observations from the graph.

2.3(c) Generally speaking, what is TCP's mode of operation most of the time to the right of the dot of interest? Briefly justify your answer. Reference both facts about the operation of TCP Tahoe and observations from the graph.

Part 3: Submission of the Report

Create and submit a written report with the content described below. Your full name, Virginia Tech PID, Virginia Tech email address, and assignment name ("ECE/CS 5565 Project 5") should appear at the top of the first page. Do *not* include your Student ID number.

Provide answers to all questions above from Part 1 (1.1-1.3) and Part 2 (2.1-2.3). In your report, provide three headings. The first two headings for Sections 1 and 2 should correspond to the headings for Parts 1 and 2 in the assignment. Under each section heading, provide answers for the questions from each part of the assignment. Include the question numbers and answer all questions in order. All answers should be concise and clear.

Include a third section in the report, "Section 3. Summary," which answers the following question.

3. Did you have any problems with the assignment, including any problems with OMNeT++/INET or Wireshark? If so, briefly describe the problems.

Your report should be submitted as a single PDF file with the following file name:

*YourLastName*_*YourFirstName*_P5.pdf

Note that "YourLastName" is your last or family name as used by Virginia Tech and that "YourFirstName" is your first or given name as used by Virginia Tech. Submit the report in the Assignments section of the class Canvas site by the due date.

Honor System Expectations

Your work on this project and your submission should be your own. You may consult with others about how to use OMNeT++/INET and Wireshark. You are encouraged to ask such questions and provide responses to such questions using the "Project 5" topic in the Discussions section of the class Canvas site. **You are not to collaborate with others on the actual analysis simulation results or trace files, providing the information for the report, or on writing the report. Such collaboration will be considered a violation of Virginia Tech's Graduate Honor Code.** Please review the section on "Graduate Academic Integrity" in the course syllabus available on the class Canvas site before you begin work on this project.

Grading Rubric

Your project will be graded using the following rubric as a guide. The maximum score is 100 points.

Project Criterion	Attributes of Strong Work	Attributes of Medium Work	Attributes of Weak Work	Maximum Points
Part 1 – Analyzing Basic Performance	The table is correct and there is a brief summary of how results were obtained. Answers to all questions are correct, complete, specific, clear, and concise. Explanations refer to results for mean and standard deviation of end-to-end delay, results for throughput, and features of the histograms. All histogram images are clear, properly labeled, and provide reasonable results. (45-50 points)	There are some minor errors or omissions with the results in the table and/or answers to questions. Explanations are correct or mostly correct, but are incomplete or overly verbose. Explanations do not refer to all of the results and/or histograms. The histogram images are not completely clear and there may be some problems with labeling. (35-44 points)	There are significant errors or omissions in the table and/or answers. Multiple explanations are incorrect or vague. Explanations do not refer to results or histograms or refer to only a small portion of the results. Histograms are missing or not legible. (0-34 points)	50
Part 2 – Analyze TCP Congestion Control Behavior	Answers to all questions are correct, complete, specific, clear, and concise. The image of the graph from Wireshark is correct and clear. (35-40 points)	There are some minor errors or omissions with answers to the questions. Explanations are or mostly correct, but are incomplete or overly verbose. The graph is included, but is not clear and/or the frame of interest is not clearly indicated. (25-34 points)	There are multiple omissions or other errors with answers to questions. Many of the explanations are incorrect or unclear. The graph is not included or does not clearly show the area before and after the frame of interest. (0-24 points)	40
Overall Presentation and Submission	Work is clearly presented and organized with headings in the correct order. Text and the images are clear and appropriately labeled. The brief summary section is provided. Submission instructions were followed. (9-10 points)	Work is mostly clear but with some lack of clarity in writing and/or the images. Organization is adequate, but not completely aligned with directions given. The summary section is missing. (6-8 points)	Work is hard to follow. Did not follow instructions for organizing the report. Did not fully follow submission instructions. The summary section is missing. (0-5 points)	10
TOTAL POINTS				100

Updates

Date	Changes
11/25/2024	Corrected question 1.3(b). Changed: “What features of TCP Tahoe help or hurt the performance of Run 3 compared to results for Run 3” to “What features of TCP Tahoe help or hurt the performance of Run 2 compared to results for Run 4.”